Cubesat Test Platform for miniaturized electric propulsion system verification campaign

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Abstract: Miniaturized electric propulsion systems are one of the major technologies that would increase the interest in CubeSats for future space missions. However, the integration of miniaturized propulsion systems in the modern CubeSat platforms presents some issues due to the mutual interactions in terms of power consumption, chemical contamination and generated thermal and electro-magnetic environments. The present paper deals with validation of a flexible test platform to assess the interaction of propulsion systems with CubeSat-technologies from mechanical, electrical, magnetic, and chemical perspectives. The test platform is a 6U CubeSat hosting an electric propulsion system and able to manage a variety of electric propulsion systems. The platform can regulate and distribute electric power (up to 60 W), exchange data according to several protocols (e.g. CAN bus, UART, I2C, SPI), and provide different mechanical layouts in 4U completely dedicated to the propulsion system. Moreover, the data gathered by the onboard sensors are fused with data of external devices and tools providing unprecedented information about the mutual behavior between a CubeSat platform and an electric propulsion system.

Nomenclature

AIV	Assembly Integration and Verification Plan
CDH	Command and Data Handling
COM SYS	Communication System
COTS	Component Off The Shelf
CTP	CubeSat Test Platform
ECSS	European Cooperation for Space Standards
EP	Electric Propulsion
EPL	Electrical Propulsion Laboratory
EPS	Electrical Power System
GSE	Ground Support Equipment
GSS	Ground Support System
LS	Loads Switch
PCB	Printed Computer Board
PPU	Power Processing Unit
PS	Propulsion System

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PWM	Pulse Width Modulation
RBT	Remove Before Test
RF	Radio Frequency
RTOS	Real Time Operating System
SPI	Serial Parallel Interface
TCS	Thermal Control System
VMU	Vitual/digital Mock-Up

I.Introduction

CubeSats were born in the university as hands-on-practice activity for students (Ref.1) but, they are becoming of interest for companies and space agencies thanks to the low cost and fast delivery paradigm that characterizes the CubeSat in any phase of the product life.

Scientific experiments and Earth observation, technological demonstrations, communication networks, and interplanetary exploration are the missions in which the new generation of CubeSat can operate both as support of bigger spacecraft and as stand-alone platforms organized in large constellations (from Ref. 2 to Ref 7)

The new generation of CubeSat requires the development of adequate technologies that enhance performance and increase mission success, just to maintain the low cost and fast schedule and time-to-orbit. Advanced communication systems with higher data rate (Ref. 8), on board computer able to manage autonomously the mission operations and the off-nominal events (Ref. 9), precise attitude control systems, navigation, thermal control systems (Ref. 10) and effective propulsion systems are the most promising technologies that would provide the quality jump to CubeSats.

In the framework of miniaturized propulsion systems, the developers of electric propulsion systems are growing. In literature, authors in Ref.11, Ref.12, Ref13 present wide overviews of the electric propulsion systems for small satellites. Despite of the large number of developers, very few CubeSats have flown up today and these systems, especially in Europe, are not still ready mainly because of a low maturity of the technologies and to the lack of a robust integration and verification process with the rest of the CubeSat. Beyond the stand-alone performance if the propulsion systems, their interactions, compatibility, and impact on the CubeSat shall be investigated and assessed to increase the confidence level in the system capabilities. The importance of a complete verification campaign is confirmed by the low success rate (around 50%) of the education CubeSats (Ref. 14), normally, dominated by infant mortality deriving from design weakness and/or ineffective assembly, integration and verification (AIV) planning and execution due to non-standardized processes and lack and/or unavailability of facilities. On the contrary, effective verification process may help to improve the reliability of small satellites (Ref. 15)

The verification and validation (V&V) process is critical both for small satellites and for Electric Propulsion (EP) System. A limited standardization of the V&V process for CubeSats is observed (Ref.16). Only in the last years some effort was made in this direction mainly providing general guidelines and advices. However, at the moment, small satellites are extensively tested only against launch environment requirements due to the request of launch authorities, On the contrary, minor efforts were made to the verification of functional and operational requirements, that are fully demanded to CubeSats developers. To reduce time and cost, in the small satellite framework, developers and integrators tend to abuse of the analysis in place of test but only part of the answers on software and hardware functionalities can be obtained. In this sense, In The Loop (ITL) simulations and tests are preferred (Ref.17) but few facilities are outfitted to host this kind of verification and rarely a CubeSat can perform both functional and environmental test in an one-stop facility. This condition is deeply true in the verification of miniaturized (electric) propulsion system point of view because severe rules (i.e. safety requirements and constraints) imposes great efforts to guarantee a complete and reliable verification process. Moreover, specific (and changing with the type of EP system) conditions are required (i.e. a vacuum environment). That result in a very expensive and time-consuming AIV. Moreover, the facilities for bigger propulsion systems are not tailored for the verification of small systems. New facilities able to perform in situ tests and diagnostics are the "Automated Integrated Robotic System for Diagnostics and Test of Electric and □-Propulsion Thruster", at Singapore (Ref 18), the Propulsion "In the Loop" test bench at University of Stuttgart (Ref. 19) and the "ESA-Prop Test Platform for CubeSat Propulsion Systems" (Ref. 20). However, all these facilities are still under preparation or certification.

Since 2017, ESA is carrying out a program with the cooperation of the Politecnico di Torino that aims at offering a one-stop test facility for the verification and validation of CubeSats with propulsion system. The objectives are the construction of a facility focused on CubeSat qualification for launch and the assessment of the impact of new technology (in particular, miniaturized electric propulsion system) on at mission and system/subsystem level. The program has been divided in three phases and, at this time, the first phase is close to the completion. In the first phase

the objective is to demonstrate the feasibility of a test platform to host miniaturized electric propulsion systems through the design, production and functional verification of a prototype (called CubeSat Test Platform, CTP) platform based on CubeSat technology, compliant with CubeSat standard and ESA Propulsion Laboratory requirements.
The present paper shows the major, actual results obtained at the actual stage of the program, highlighting verification and validation process of the CTP, that is now ready to integrate EP systems.

II. Objectives and CTP design

A. Objectives and requirements

Two objectives are pursued with the project:

• OBJ1: To design and build a prototype CubeSat Test Platform (CTP) based on COTS technology suitable for hosting and handling miniaturized electric propulsion systems

• OBJ2: To define a procedure for testing the integrated CTP/electric propulsion system in a relevant environment (@ESA/ESTEC EPL)

Propulsion system could be assessed along several metrics, including thrust levels, mass, power consumption, specific impulse, total impulse per unit system wet mass ratio, total impulse per unit system volume ratio, and thrust to power ratio. In general, a test campaign fulfilling the abovementioned objectives and requirements would include the measurement of several parameters, at subsystem and system level. That implies the need of a large range of sensing equipment hosted on the CTP.

For the purpose of the research program, a 6U CubeSat is considered as a reference size that would allow to host a large range of EP systems giving the possibility to add sensors and tools inside the platform that are not traditionally part of a CubeSat. The considerations and the obtained results can be suitable or scalable for other CubeSat form factors (i.e. form 3U up to limits of the standard) without lack of consistency.

A set of miniaturized electric propulsion system are considered for the development of the CTP in order to meet the functional, physical, and interface requirements imposed by the as wide as possible range of EP system based on different technologies.
The main EP system analyzed are:

- Enpulsion – Austria IFM - FEEP.
- ThrustMe – France NPT30 - Gridded ion thruster
- ExoTrail – France EXO-Hall effect thrusters
- T4I – Italy Regulus
- Institute of Space Systems (IRS) at University of Stuttgart – Germany PETRUS - PPT
- GOMSPACE – Denmark HiperLoc-EP – Electrospray
- Busek Co Inc -USA BET – Electrospray
- ACCION – USA IET5000 - Electrospray

Moreover, some key features drive the design of the platform:

1) **Safety:** to prevent leakage of fluids and contamination, over-voltages and over-currents, too high and low temperatures and electromagnetic interference.
2) **Reliability**: to guarantee that the functionalities of the CTP are available in case of misbehaviors
3) **Flexibility**: to get the possibility to host EP system in different configurations
4) **Accessibility**: to facilitate the operations of the operators in any phase of the AIV process
5) **Autonomy**: to guarantee that CTP mainly operates without the interventions of the operators
6) **Cost**: to maintain the cost of the process low.

B. Design

CTP functional architecture at equipment level is presented in Figure 1 (red lines are the electrical lines, blue lines the data link and black lines the mechanical connections). Propulsion system exchanges data with the Command and Data Handling (CDH), receives the power through a dedicated voltage-regulated line from Electrical Power System (EPS) and is mechanically connected to primary and secondary structure. The structure is fully compliant with the Cubesat Design Specification (CDS) for 6U platforms in terms of external geometrical interface and material (apart from surface coatings and treatments). The internal layout is adapted according to the specific test: a bulkhead separates the propulsion box from the rest of the platform. The EP system under test is mounted on this bulkhead, with the thrust axis along the X geometrical axis of the satellite. The avionic subsystems are in the avionic box and interfaced with other onboard elements and Ground Support Equipment (GSE) through connectors. Avionics subsystems are based on self-developed electronic boards resulting representative of the basic CubeSat technology. Two lines guarantee communications between the platform and EPL operators, a Radio-Frequency (RF) link in UHF band and a wired hardline serial line that directly connect the onboard computer with the Ground Support System (GSS). CDH is based on ARM-9 microcontroller that manages data and commands, on-board time and synchronization, operations and on-board failures. Sensors and acquisition circuits provide the information (e.g. voltages, currents, temperatures, accelerations, magnetic fields, and electrical fields). EPS is constituted by a motherboard that controls and distributes power to the other subsystems, and manages PS battery recharging, and a daughter board that manages the avionics battery packs recharging. Moreover, the EPS hosts a Step-Up circuit that adapts the PS battery voltage in the range 5-28 V providing a maximum power in output of 60 W. The delivered and power is then managed by the PPU of the EP system. Four switches control the activation of the CTP: two switches inhibit the connection of the battery packs to the bus when the CTP is not in use and during the transportation. Other two switches separate all the loads from the power bus.

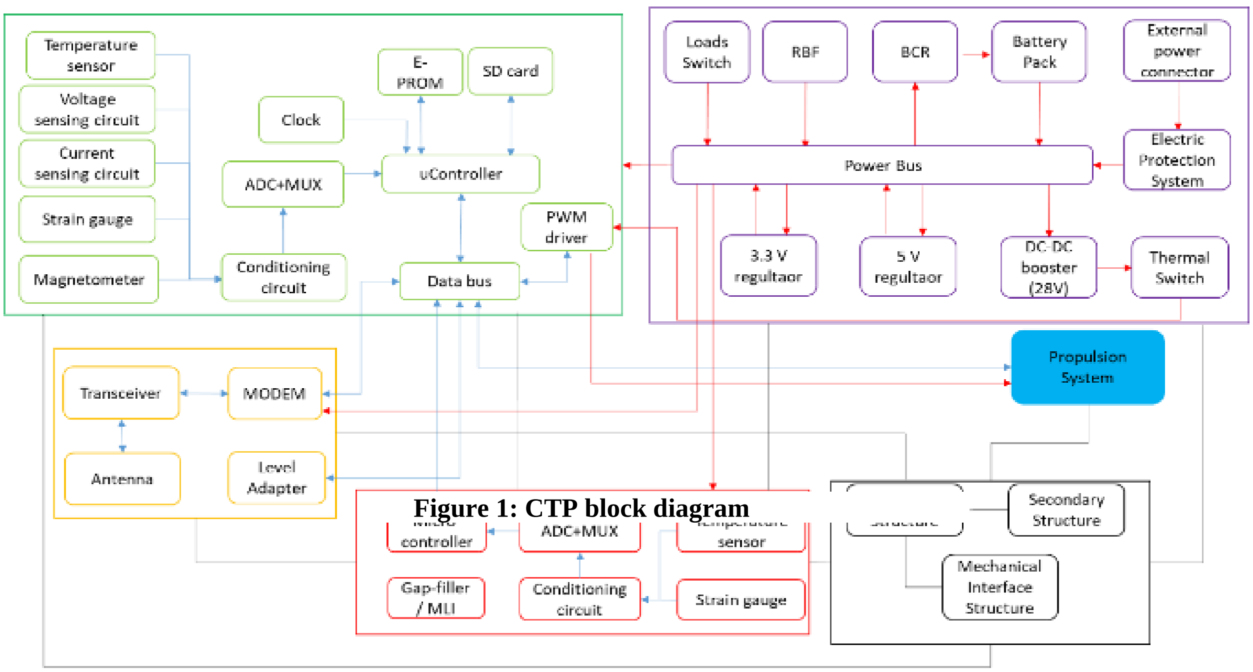

Figure 1: CTP block diagram

The physical layout of the CTP is constituted by two main parts, contained in a 6U structure. The *PS box* is a module with dimension up to 4 U where the EP system is located. A bulkhead used to fix the PS to the structure and to interface the PS with the Service Module permits flexible internal layout according the EP system configuration. The *Service module* contains the avionics subsystems and equipment supporting the tests execution. All the avionics subsystems (CDH, Communication System (COM SYS), EPS – mother-board, EPS daughter board) stay in the *avionics box*. The boards are connected through a 104-pin bus for electrical power supplying and data exchange and are mounted on a stack of four bars that fix the *avionics box* to the primary structure.

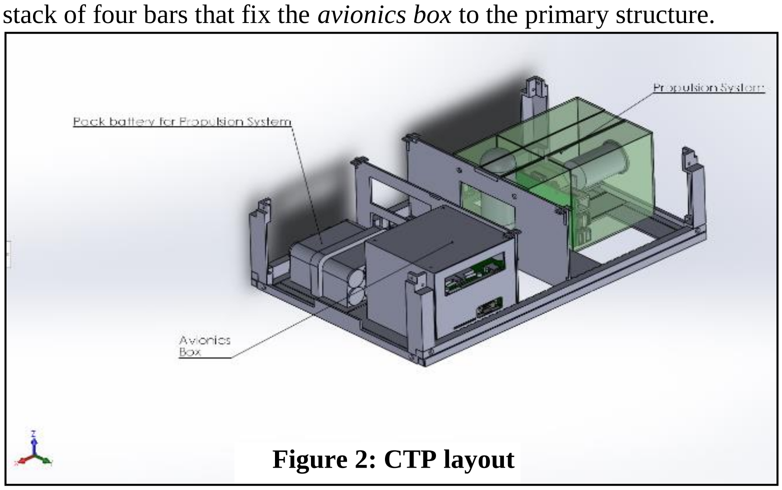

Figure 2: CTP layout

The external interfaces (battery packs recharging ports, hardline data connectors, and switches) are available on the +Y face. The electrical and data interfaces towards the PS are located on the other side of the avionics box. The dipole antenna of the COM SYS is mounted on the +Z face. The entire *avionics box* occupies a 1U on the +X/+Y side of box. The side +X/-Y is allocated to the PS battery packs.

Mechanical and electrical protections elements are inserted in the design. Fault avoidance (high-quality parts and appropriate design margins), and fault tolerance (redundancy) approaches are implemented at least for safety-critical functions (e.g. thermal switches). The system can execute the test tolerating at least one system failure for a set of relevant functions. Moreover, the CTP is intended for use in a test facility with adequate GSE and skilled operators to conduct the test. However, a high-degree of autonomy of the CTP is foreseen in order to increase the value of the project in terms of fidelity with respect to a real case (i.e. CubeSat in orbit) and also to reduce the effort and workload of operators.

1. CTP operative modes

Five operative modes of the CTP are defined in order to cover all the phases of the tests:

- **Dormant.** CTP is switched-off.
- **Basic mode.** CTP avionic subsystems are active, PS is switched-off.
- **PS mode:** CTP avionics subsystems are active, Propulsion System is switched-on but thruster is off.
- **Burst mode:** Thruster is activated.
- **Safe mode:** CTP avionics subsystems are active and recovery actions are performed.

Transition between operative modes can be autonomously executed by the CTP and/or can be commanded from ground. In the Figure 3, red lines indicate a transition made with the intervention of the operator, green lines autonomous transitions, and blue lines transitions that could be made autonomously and/or with the operator intervention. Manual transitions are foreseen when a high risk for CTP and GSS/EPL-GSE occurs and the platform must switch off. CTP avionics, PS and thruster burst can be activate/deactivated both with a command from the GSS or directly by the platform when well-identified conditions are checked. Transitions due to off nominal conditions are managed autonomously by the CTP, while transitions after recovery routine completion in Safe Mode can be performed both by the operator and directly by the CTP.

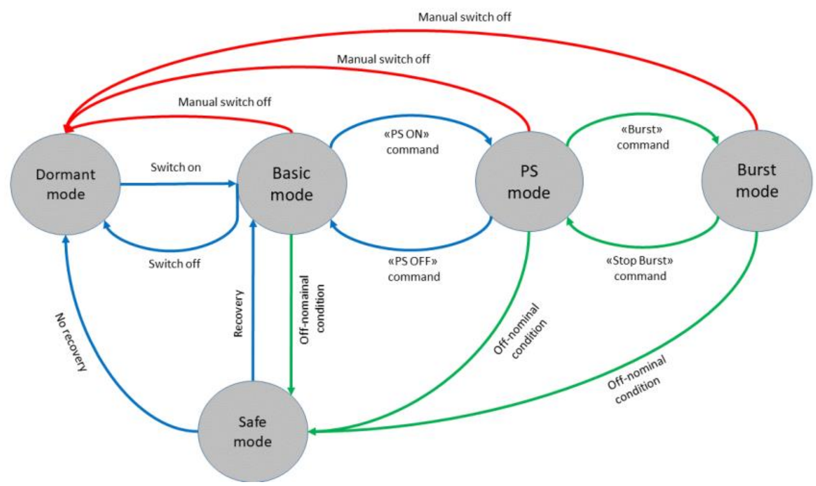

Figure 3: CTP operative modes

III.Verification process

This section presents the step-by-step procedure to assembly, integrate and verify the CTP up to the delivery at ESA/ESTEC.

As shown in Figure 4, the planned verifications are:

1. **Interface Test**. All the interfaces and protocols are under test: The adopted interfaces are UART (three communication lines set with RS232 protocol – one is the hardline, the second connects the CDH and the COMSYS and the third is optional towards the EP system), SPI bus to communicate with the data acquisition circuits, and I2C bus towards the magnetometer.

2. **Acquisition test**. This test aims at the validation of the software units and hardware circuits taking care of acquiring data from sensors and setup the data exchange with EP system. A 16-channels ADC is mounted on the CDH and the acquired data acquisition of temperatures and magnetic field shall be consistent.

3. After the integration of the SD-card into the dedicated slot on CDH board, the **Storage test** aims at verifying the capability to store data in the non-volatile memories (both SD-card and an EPROM).

4. **Communication test**. This test deals with the validation of the software units and hardware for communication via hardline and RF link. The COMSYS board is integrated with the CDH and the GSS is prepared in order to

guarantee the exchange of data and commands. Moreover, the consistency of the packets with the CRC (Cyclical Redundancy Code) shall be confirmed.

5. **PWM test**. This test aims at confirming the capability of the CDH to communicate with EPS and set-up the voltage on the power output towards the EP system through the Step-up circuit. The CDH shall demonstrate the capability to control the voltage according to the request of the EP system under test.

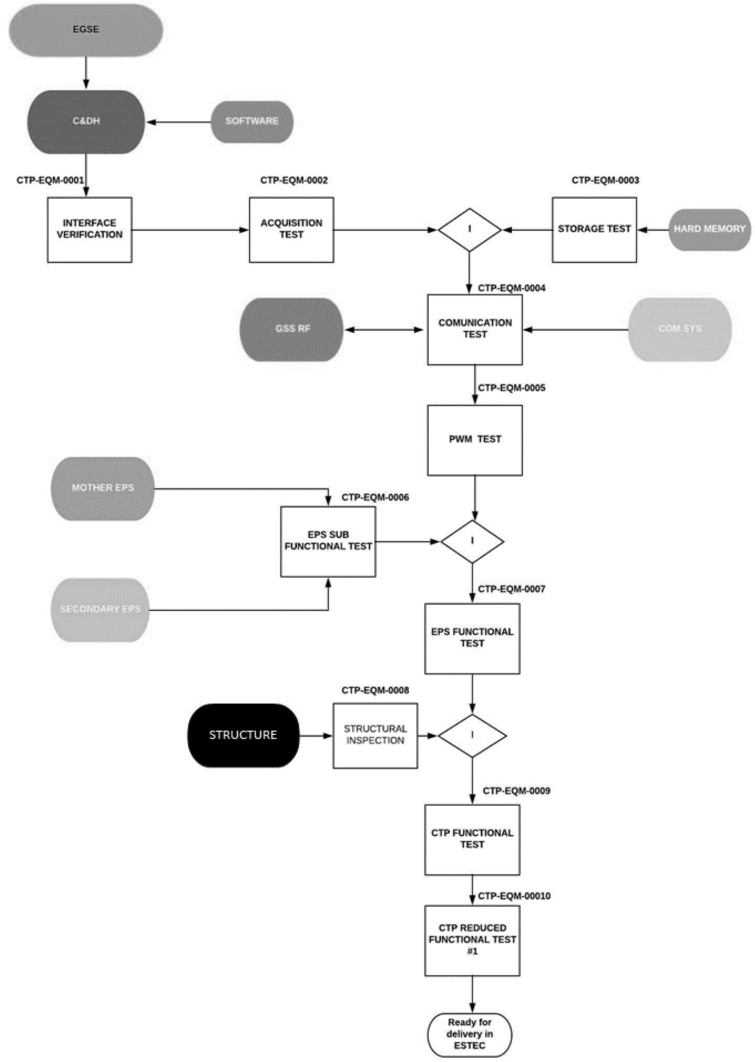

Figure 4: AIV step-by-step procedures

6. **EPS test**. This test shall verify the capabilities of the EPS system stand-alone (i.e. without any other subsystem). Going into details, the motherboard EPS (EPS.M) is tested to demonstrate the ability of regulation of the bus voltages (3.3 V and 5 V), and control of the discharging and the recharging of the Propulsion Battery packs. The same capability is expected for the daughter EPS (EPS.D): regulation of the voltage outputs, and control of the discharging and the recharging of the Avionics Battery packs. Then the two board are integrated with the CDH and COM SYS sub-assembly completing integration of the avionics box.

7. The **Structure verification** is performed: in particular, the primary structure is inspected and then the mechanical properties confirmed, taking care the compliance with the CDS.

8. **Full functional test**. The functions that CTP shall accomplish to reach the goals of the program shall be tested in a single, global test. They include not only the confirmation of the already tested functionalities but also the verification at system level such as the capability to operate in the different operative modes and during transitions from one mode to another. This test was led before the integration of any EP system in the CTP. However, the EP system electrical and thermal behaviors are (partially) reproduced using a strip of resistors distributed on an aluminum cylinder. In particular, the first resistor (RL1) is installed in the position of the expected output of the thruster, the second resistor (RL2) in the middle of the cylinder and the third resistor (RL3) on the power supply input from the EPS. For the case presented in this paper, the voltage applied to the resistors is 28 V (the worst case for this version of CTP). Moreover, an external PC emulates the data exchange with EP system: in particular, a dedicated software is able to generate a stream of bytes (simulating the behavior of the CPU of the EP system) that the CDH acquires and handles.

9. **Reduced Functional Test**. The reduced functional test (RFT) are performed to check the main capabilities of CTP and GSS (details are provided in the next paragraph) after major events, for example, before the transportation and the delivery at ESA/ESTEC.

IV.Results

In this section, the main results of the AIV campaign on the EQM are reported. The focus is posed on the outputs of the full functional test because all the main functionalities and the major part of requirements are verified though this test. This test foresees the following steps:

- Communication and data acquisition in "basic mode": the housekeeping telemetry data are available but no info is gathered on propulsion system that is power-off.
- Activation of the propulsion system, before, and the simulation of the thruster activation, then, are commanded from ground. Moreover, the data from the emulated PS are acquired and saved on board.
- De-activation of the propulsion system, stopping the thruster simulation, before, and the entire propulsion system, after. At the end, the CTP operates again in basic mode.
- Verification of the main commands, all the command to control the nominal and off-nominal conditions are checked.

C. Communication, data handling and storage

The two communication lines towards GSS (and the operator) received all the packets without errors in the signal reception and data decoding.

Figure 5 shows the evolution of the number of packets for each line: in nominal mode, 12 packets/minute are sent via Hardline while 2 packets/min is the rate of transmission for the RF link.

The storage capability is demonstrated because both on the EPROM and SD card the packets are saved without discrepancies or errors.

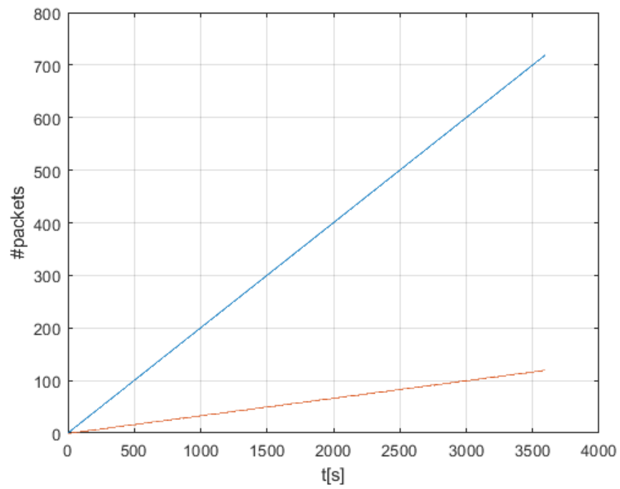

Figure 5: number of packets

D. Data acquisition

Data acquisition is a crucial function because all the measurements and information are fundamental for the process of CTP validation and, then, for the qualification of the EP systems.

There are three categories of data acquired on the CTP:

- Housekeeping data: 5V Bus, 3.3 V Bus currents, Avionics battery packs and Propulsion battery packs information in terms of voltages, currents, temperatures, and recharging currents are provided.
- PS data: information that the EP system sends through a dedicated digital interface (e.g. USB, UART, SPI, and I2C)
- Test data: measurements of mutual impact between EP system and CTP accomplished with on board sensors / devices and tools by CTP:
    - Temperatures: 10 NTC sensors are installed in different parts of CTP to monitor the variations in different operative modes
    - Magnetic field: 1 triaxial magnetometer posed inside the avionics box to capture change in the magnetic field in different operative modes
    - Voltages and currents: voltage and currents sensing circuits provide information about the consumption of the EP system under test.

These measurements will be merged in post processing with the measurements of the GSE provided by ESA and installed inside the chamber. To have a complete information suite, sensors and tools (which are part of the GSE), installed outside and with no direct interaction with the CTP, are included in the set-ups. Torsional thrust balance allows obtaining the thrust values). Mass flow sensors provide information to determine the mass flow rates. Microscopes and spectrometers are used in post processing to analyze the chemical residual on the CTP surfaces. A

Quartz Crystal Microbalance measures the propellant mass variation per area. Amperometers and voltmeters, thermocouples, and a Magnetic Field Mapper add other measurements of current, voltage, temperature and magnetic field beyond the CTP measurements. Faraday cups and Langmuir probes provide information for plasma analyses, if necessary. All these data are post-processed to have a completed overview of the behavior both of the EP system and CTP. The huge number and type of available sensors allow different set-ups, e.g. CTP can be mounted on a torsional balance or in a thrust stand.

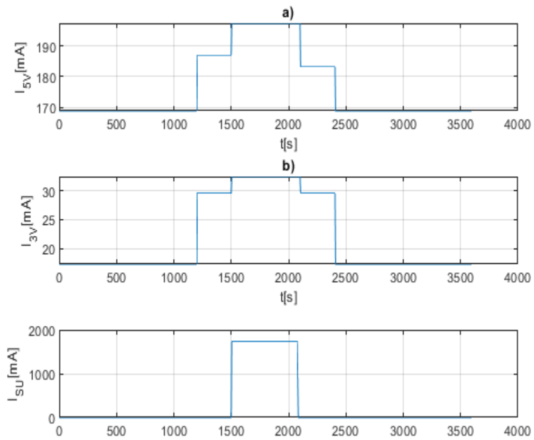

Figure 6: onboard power consumptions

Figure 7 reports the power consumption on, 5 V bus, 3.3V bus and in output of the step-up circuit (about 28 V) with respect to the operative modes: at the beginning (from minute 0 to minute 20) and in the last part of the test (from minute 40 to minute 60) the *basic mode* (OM#1) is active. From minute 20 to minute 25 and from minute 35 to minute 40 the *PS mode* (OM#2) is active, and from minute 25 to minute 35 the *burst mode* (OM#3) is active. The consumption of 3.3V bus (graph (b)) stays in the range 18-32 mA and the consumption of 5V (graph (a)) remain in the range of 171-198 mA that are values within the imposed constraints on the power consumption and acceptable for the avionics system of a 6U platform. In basic mode, only the avionics is active: in particular, all the acquisition lines and the ARM-9 for CDH, the COM SYS board (MODEM and radio-module both in reception and in transmission), and the regulation circuits of the EPS. The increments of consumption in OM#2 and OM#3 is due to the activation of peripherals on CDH and supplying lines on EPS towards the EP system interfaces. The consumption on the Step-Up line (graph (c)) depends only to the activation of burst mode). In this test, a voltage of 28 V is applied with a peak 1880 mA, showing the capability of the CTP to work properly the defined worst case (see requirements in Table 2).

E. Battery packs management

Figure 6 shows the data of the Avionics (AV) battery packs: battery packs voltages is decreasing, while the currents change according to the operative modes. The temperature (measured by the NTC installed inside the battery pack, between the two Li-Ion cells) slightly increases in the first part of the test while decrease in the second part: the peak values are reached at the end of the burst phase.

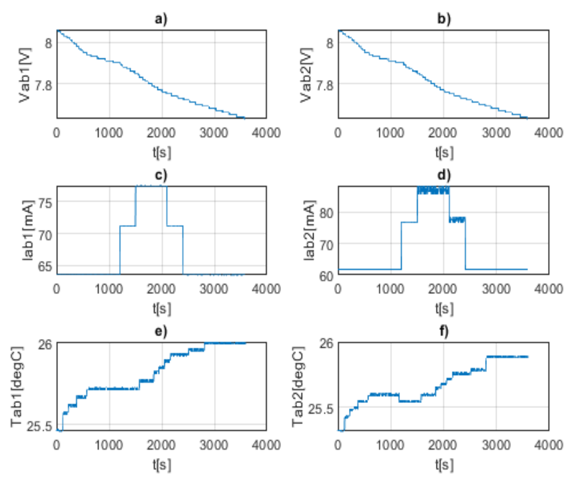

Figure 7: Avionics battery packs telemetry

Figure 8 shows that no power is required to the PS battery when the EP system (or the simulated loads) are powered off. When the burst mode starts, the voltages decrease, and the temperatures increase up to a maximum temperature if about 26 degC. When the the burst mode ends, the voltage slightly increases because the Step-up Circuit is switched off and no loads are connected to the PS battery packs. At the same time, the temperatures decrease and return around the initial values.

All the temperature sensors are calibrated using a reference thermo-couple, certified for the measurements in the range -40 degC to 350degC, with an accuracy of 0.1 degC. The calibration was performed in a thermal chamber using the avionics system (protected in a thermal isolated box), the NTCs and the certified thermocouple.

F. Internal temperature

Figure 9 presents the temperature measured on the processor, the transmitter, the Step-Up circuit and the bulkhead from the side of the service module. The temperatures on the processor (graph (a)) and bulkhead (graph (b)) remain almost constant for the entire test duration while the transmitter temperature increases but remains under the 40°C that is the operative limit for the component (graph (c)). The temperature on the Step-Up circuit has a quick increment (graph (d)) due to the delivery of power to the resistors RLs during the OM#3 but it returns to the initial values in less than 5 minutes after the OM#3 deactivation.

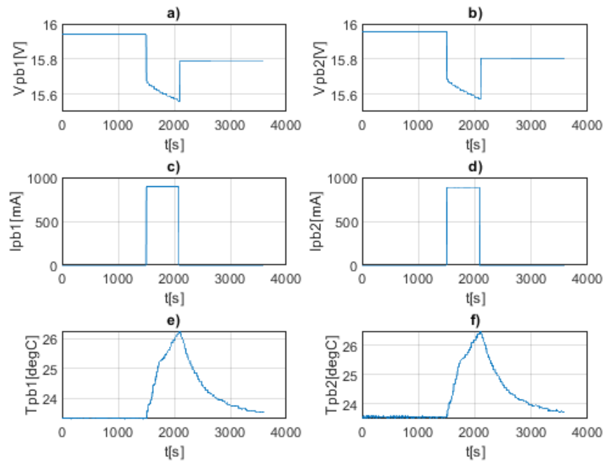

Figure 8: Avionics battery packs telemetry

V.Conclusion

The work presented in this paper aims at providing a practice solution to verify a CubeSat equipped with EP system. In particular, the objective is to assess the mutual effects between the platform bus and the propulsion system.

The platform allows performing a complete validation campaign of the entire system evaluating its efficiency through the merging of measurements obtained by sensors mounted inside and outside the CTP. Information about electromagnetic compatibility, thermal environment induced by the operations of the subsystems (specifically, of the propulsion system), and l power consumption are combined in order to provide an unprecedented framework to developers of EP system and CubeSat platforms, thus facilitating the transition of products from lab to market.

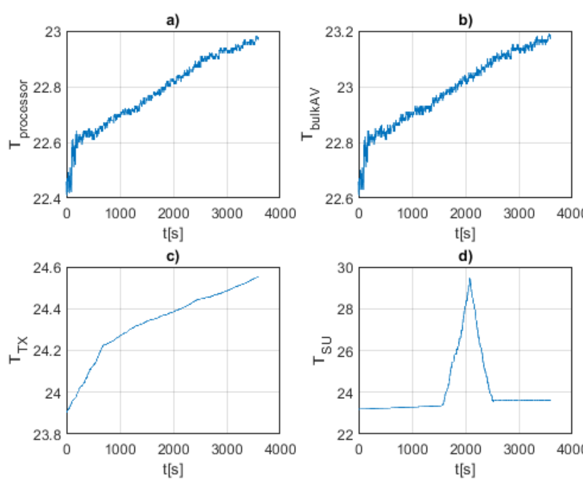

Figure 9: temperatures inside the service module

The platform is a valuable instrument to increase the level of readiness of new technology and consolidate the capability and robustness of already available CubeSat equipment and subsystems. In the context of the proposed research, future efforts will be addressed to raise the quality and quantity of provided data, adding new sensors and acquisition instruments, to improve the flexibility of the interfaces, to support the functional tests on torsional balance, and to extend the test objects range to a wider type of CubeSat technologies.

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